Claims

WE CLAIM:

1. A method for controlling a reciprocating pump comprising two cylinders with associated pistons, one discharge check valve for each cylinder, and at least one closed interval $[\alpha_0, \alpha_2]$ where α is an angular displacement, α_0 is an angular displacement when a first piston is at bottom dead center, and α_2 is an angular displacement when a second cylinder's discharge check valve closes; the method comprising the steps of:

(a) operating the reciprocating pump at a constant angular speed except through the closed interval between the angular displacement when the first piston is at bottom dead center and the angular displacement when the second cylinder's discharge check valve closes, $[\alpha_0, \alpha_2]$; and

(b) varying an angular speed of the reciprocating pump to maintain a constant pump discharge pressure through the closed interval $[\alpha_0, \alpha_2]$.

2. The method of claim **1** wherein, in a single pump cycle, there are two closed intervals, $[\alpha_0, \alpha_2]$ and $[\alpha_4, \alpha_6]$ within which the angular speed of the reciprocating pump is varied to maintain a constant discharge pressure and where α_4 is an angular displacement when a second piston is at bottom dead center, and α_6 is an angular displacement when a first cylinder's discharge check valve closes.

3. The method of claim **1** wherein an upper angular displacement limit, α_2, on the closed interval $[\alpha_0, \alpha_2]$ is determined by the steps:

(a) measuring the pump discharge pressure;

(b) measuring the angular displacement, α, of the pump;

(c) calculating a first time derivative of the pump discharge pressure; and

(d) storing a value of the angular displacement, α_2, of the pump when the first time derivative increases sharply.

4. The method of claim **3** wherein the pump angular speed is held constant during the determination of α_2.

5. The method of claim **1** wherein a lower limit α_0 on the closed interval $[\alpha_0, \alpha_2]$ is determined by a cam sensor.

6. The method of claim **1** wherein the discharge check valves are instrumented to indicate their open and closed states and an upper limit α_2 on the closed interval $[\alpha_0, \alpha_2]$ is determined by the steps:

(a) monitoring signals from the two discharge check valves; and

(b) storing a value of the angular displacement, α_2, of the pump when the check valve closes.

7. The method of claim **1** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and wherein a pressure set point for the pressure controller is a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_2]$.

8. The method of claim **2** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and wherein a pressure set point for the pressure controller is a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_6]$.

9. The method of claim **1** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and, wherein a pressure set point for the pressure controller is an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_2]$.

10. The method of claim **2** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and, wherein a pressure set point for the pressure controller is an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_6]$.

11. The method of claim **1** wherein a pumping system also includes a valve tree comprising two three-port solenoid valves operating in a cycle to measure three solvents into the pump, said method comprising the steps of:

(a) configuring said valves such that no more than one path between the three solvents and the pump may be open at a time;

(b) actuating said valves within the valve tree sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said three solvents into the pump through the valve tree; and

(c) deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

12. The method of claim **11** wherein each valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

13. The method of claim **1** wherein a pumping system also includes a single solenoid actuated valve comprising a plurality of inlet ports and a single outlet port, the method comprising the steps of:

(a) connecting the plurality of inlet ports to a plurality of solvents; and

(b) actuating said valve, switching between said inlet ports, sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into

the pump.

14. The method of claim **13** wherein the valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

15. The method of claim **1** wherein a pumping system also includes a plurality of two-way valves and number of solvents equal to a number of the plurality of two-way valves, said method comprising the steps of:

(a) connecting an inlet port of each of said plurality of valves to one of said plurality of solvents;

(b) actuating at most only one valve at a time;

(c) actuating said plurality of valves sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump; and

(d) deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

16. The method of claim **11** wherein each valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

17. A method for controlling a reciprocating pump comprising two cylinders with associated pistons, one discharge check valve for each cylinder, and at least one closed angular displacement interval $[\alpha_0, \alpha_3]$ where α is an angular displacement, α_0 is an angular displacement when a first piston is at bottom dead center, and α_3 is an angular displacement when a second cylinder's inlet check valve opens; the method comprising:

(a) operating the reciprocating pump at a constant angular speed except

through the closed angular displacement interval between a displacement when the first piston reaches bottom dead center and a displacement at an opening of the second cylinder's inlet check valve, $[\alpha_0, \alpha_3]$; and

(b) varying an angular speed of the reciprocating pump to maintain a constant pump discharge pressure through the closed interval $[\alpha_0, \alpha_3]$.

18. The method of claim **17** wherein, in a single pump cycle, there are two closed intervals, $[\alpha_0, \alpha_3]$ and $[\alpha_4, \alpha_7]$ within which the angular speed of the reciprocating pump is varied to maintain a constant discharge pressure and where α_4 is an angular displacement when a second piston is at bottom dead center, and α_7 is an angular displacement when a first cylinder's inlet check valve opens.

19. The method of claim **17** wherein an angular displacement upper limit, α_3, on the closed interval $[\alpha_0, \alpha_3]$ is determined by the steps:

(a) determining a recompression volume for the pump cylinder;

(b) determining a decompression volume as a function of the recompression volume; and

(c) correlating the decompression volume to the angular displacement upper limit, α_3.

20. The method of claim **17** wherein a lower limit α_0 on the closed interval $[\alpha_0, \alpha_3]$ is determined by a cam sensor.

21. The method of claim **17** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and wherein a pressure set point for the pressure controller is a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_3]$.

22. The method of claim **18** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and wherein a pressure set point for the pressure controller is a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_7]$.

23. The method of claim **17** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and, wherein a pressure set point for the pressure controller is an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_3]$.

24. The method of claim **18** including a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated, and, wherein a pressure set point for the pressure controller is an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_7]$.

25. The method of claim **17** wherein a pumping system also includes a valve tree comprising two three-port solenoid valves operating in a cycle to measure three solvents into the pump, said method comprising the steps of:

(a) configuring said valves such that no more than one path between the three solvents and the pump may be open at a time;

(b) actuating said valves within the valve tree sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said three solvents into the pump through the valve tree; and

(c) deactivating all valves simultaneously during a time in which both

pump inlet check valves are closed.

26. The method of claim **25** wherein each valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

27. The method of claim **17** wherein a pumping system also includes a single solenoid actuated valve comprising a plurality of inlet ports and a single outlet port, the method comprising the steps of:

(a) connecting the plurality of inlet ports to a plurality of solvents; and

(b) actuating said valve, switching between said inlet ports, sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump.

28. The method of claim **27** wherein the valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

29. The method of claim **17** wherein a pumping system also includes a plurality of two-way valves and number of solvents equal to a number of the plurality of two-way valves, said method comprising the steps of:

(a) connecting an inlet port of each of said plurality of valves to one of said plurality of solvents;

(b) actuating at most only one valve at a time;

(c) actuating said plurality of valves sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump; and

(d) deactivating all valves simultaneously during a time in which both

pump inlet check valves are closed.

30. The method of claim **29** wherein each valve is sequentially activated at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

31. An apparatus for controlling a reciprocating pump comprising two cylinders with associated pistons, one discharge check valve for each cylinder, and at least one closed interval $[\alpha_0, \alpha_2]$ where α is an angular displacement, α_0 is an angular displacement when a first piston is at bottom dead center, and α_2 is an angular displacement when a second cylinder's discharge check valve closes; the apparatus comprising:

(a) a constant angular speed control loop for operating the reciprocating pump at a constant angular speed except through the closed interval between the angular displacement when the first piston is at bottom dead center and the angular displacement when the second cylinder's discharge check valve closes, $[\alpha_0, \alpha_2]$; and

(b) a constant pressure control loop for varying an angular speed of the reciprocating pump to maintain a constant pump discharge pressure through the closed interval $[\alpha_0, \alpha_2]$.

32. The apparatus of claim **31** additionally comprising means for maintaining a constant discharge pressure in a second closed interval, $[\alpha_4, \alpha_6]$, within which the angular speed of the reciprocating pump is varied to maintain a constant discharge pressure and where α_4 is an angular displacement when a second piston is at bottom dead center, and α_6 is an angular displacement when a first cylinder's discharge check valve closes.

33. The apparatus of claim **31** including steps to determine an angular displacement upper limit α_2 on the closed interval $[\alpha_0, \alpha_2]$, said apparatus comprising:

(a) a pressure sensor for measuring the pump discharge pressure;

(b) an angular displacement sensor for measuring the angular displacement, α, of the pump;

(c) a computer for calculating a first time derivative of the pump discharge pressure; and

(d) memory for storing a value of the angular displacement, α_2, of the pump when the first time derivative increases sharply.

34. The apparatus of claim **33** including means to maintain the angular speed of the pump constant during the determination of α_2.

35. The apparatus of claim **31** including a cam sensor to sense a lower limit α_0 on the closed interval $[\alpha_0, \alpha_2]$.

36. The apparatus of claim **31** additionally comprising:

(a) sensors on the discharge check valves to indicate their open and closed states; and

(b) memory for storing a value of the angular displacement, α_2, of the pump when one of the sensors indicates the discharge check valve is closed.

37. The apparatus of claim **31** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_2]$, said value of pressure to be used as a pressure set point.

38. The apparatus of claim **32** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_6]$, said value of pressure to be used as a pressure set point.

39. The apparatus of claim **31** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure as an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_2]$, said value of pressure to be used as a pressure set point.

40. The apparatus of claim **32** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure as an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_6]$, said value of pressure to be used as a pressure set point.

41. The apparatus of claim **31** additionally comprising:

(a) a valve tree comprising two three-port solenoid valves operating in a cycle to measure three solvents into the pump wherein the valves are configured such that no more than one path between the three solvents

and the pump may be open at a time;

(b) actuators for actuating said valves within the valve tree sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said three solvents into the pump through the valve tree; and

(c) deactivation logic for deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

42. The apparatus of claim **41** additionally comprising delay time measurement sensors to sequentially activate each valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

43. The apparatus of claim **31** additionally comprising:

(a) a single solenoid actuated valve comprising a plurality of inlet ports and a single outlet port;

(b) an actuator for actuating said valve, switching between said inlet ports, sequentially; and

(c) an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump.

44. The apparatus of claim **43** additionally comprising delay time measurement sensors to sequentially activate the valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

45. The apparatus of claim **31** additionally comprising:

(a) a plurality of two-way valves;

(b) a number of solvents equal to a number of the plurality of two-way valves;

(c) a number of actuators equal to the number of the plurality of two-way valves, said actuators actuating at most only one valve at a time;

(d) an associated valve actuation logic controller for actuating said plurality of valves sequentially to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump; and

(e) deactivation logic for deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

46. The apparatus of claim **45** additionally comprising delay time measurement sensors to sequentially activate the valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

47. An apparatus for controlling a reciprocating pump comprising two cylinders with associated pistons, one discharge check valve for each cylinder, and at least one closed interval $[\alpha_0, \alpha_3]$ where α is an angular displacement, α_0 is an angular displacement when a first piston is at bottom dead center, and α_3 is an angular displacement when a second cylinder's inlet check valve opens; the apparatus comprising:

(a) a constant angular speed control loop for operating the reciprocating pump at a constant angular speed except through the closed interval between the angular displacement when the first piston is at bottom dead center and the angular displacement when the second cylinder's inlet check valve opens, $[\alpha_0, \alpha_3]$; and

(b) a constant pressure control loop for varying an angular speed of the reciprocating pump to maintain a constant pump discharge pressure through the closed interval $[\alpha_0, \alpha_3]$.

48. The apparatus of claim **47** additionally comprising means for maintaining a constant discharge pressure in a second closed interval, $[\alpha_4, \alpha_7]$, within which the

angular speed of the reciprocating pump is varied to maintain a constant discharge pressure and where α_4 is an angular displacement when a second piston is at bottom dead center, and α_7 is an angular displacement when a first cylinder's inlet check valve opens.

49. The apparatus of claim **47** additionally comprising:

(a) sensors for determining a recompression volume for the pump cylinder;

(b) a first computing function for determining a decompression volume as a function of the recompression volume; and

(c) a second computing function for correlating the decompression volume to the angular displacement upper limit, α_3, said angular displacement being an upper limit on the closed interval $[\alpha_0, \alpha_3]$.

50. The apparatus of claim **48** including means to maintain the angular speed of the pump constant during the determination of α_3.

51. The apparatus of claim **47** including a cam sensor to sense a lower limit α_0 on the closed interval $[\alpha_0, \alpha_3]$.

52. The apparatus of claim **47** additionally comprising:

(a) sensors on the discharge check valves to indicate their open and closed states; and

(b) memory for storing a value of the angular displacement, α_3, of the pump when one of the sensors indicates the inlet check valve is open.

53. The apparatus of claim **47** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_3]$, said value of pressure to be used as a pressure set point.

54. The apparatus of claim **48** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_7]$, said value of pressure to be used as a pressure set point.

55. The apparatus of claim **47** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure as an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_0, \alpha_3]$, said value of pressure to be used as a pressure set point.

56. The apparatus of claim **48** additionally comprising:

(a) a pressure controller to calculate a variable angular speed set point, ω_{spp}, at which angular speed the pump will be operated; and

(b) a pressure set point calculator for determining a value of pressure as an average of a plurality of values of pressure, all measured when the angular displacement, α, is not in the closed interval, $[\alpha_4, \alpha_7]$, said value of pressure to be used as a pressure set point.

57. The apparatus of claim **47** additionally comprising:

(a) a valve tree comprising two three-port solenoid valves operating in a cycle to measure three solvents into the pump wherein the valves are configured such that no more than one path between the three solvents and the pump may be open at a time;

(b) actuators for actuating said valves within the valve tree sequentially with an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said three solvents into the pump through the valve tree; and

(c) deactivation logic for deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

58. The apparatus of claim **57** additionally comprising delay time measurement sensors to sequentially activate each valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

59. The apparatus of claim **47** additionally comprising:

(a) a single solenoid actuated valve comprising a plurality of inlet ports and a single outlet port;

(b) an actuator for actuating said valve, switching between said inlet ports, sequentially; and

(c) an associated valve actuation logic controller to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump.

60. The apparatus of claim **59** additionally comprising delay time measurement sensors to sequentially activate the valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.

61. The apparatus of claim **47** additionally comprising:

(a) a plurality of two-way valves;

(b) a number of solvents equal to a number of the plurality of two-way valves;

(c) a number of actuators equal to the number of the plurality of two-way valves, said actuators actuating at most only one valve at a time;

(d) an associated valve actuation logic controller for actuating said plurality of valves sequentially to time actuation of each valve to sequentially meter each of said plurality of solvents into the pump; and

(e) deactivation logic for deactivating all valves simultaneously during a time in which both pump inlet check valves are closed.

62. The apparatus of claim **61** additionally comprising delay time measurement sensors to sequentially activate the valve at a time corrected by measuring a delay time between electrical activation and fluid path transfer.